Analog Electronic Circuits
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Lecture - 08
Revisiting BJT Characteristic (Contd.)

So, welcome back to this program. So, what we have done in the previous class it is; we have looked into the BJT characteristic; in fact, we have started and today we are going to continue and we will try to consolidate the I-V characteristic. So, we do have some extent we have a discussed on about the working principle today will be going further detail and we will consolidate the I-V characteristic equation. So, what we have today the today's plan to cover it is the following.

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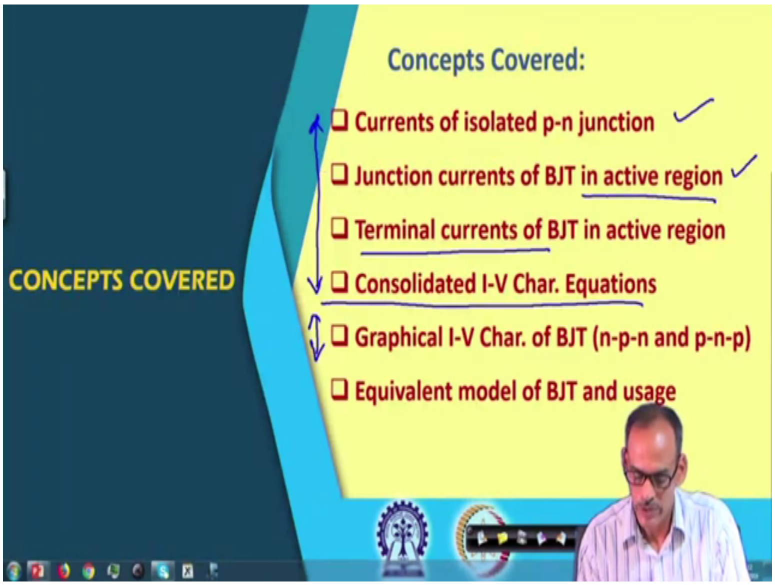

We will start with whatever the things we have discussed in the previous class namely the current in through p-n junction in isolated condition both for forward biased and reverse bias. And, then we will be going through the junction current of BJT particularly if the two junctions one is in forward bias another is in reverse bias namely in active region of operation.

Then what may be their junction currents and then using that information will be consolidating to get the terminal current of the BJT in active region of operation and from that we will consolidate the I-V characteristic equations of BJT; particularly for n-p-n transistor. And then later we will be moving to the further utilization of those I-V characteristic namely what may be the graphical interpretation of the I-V characteristic and then how do we draw the equivalent circuit of the BJT and so and so on.

So, we may have to split the whole plan; one is the part one and then we do have the part two and as I say that this part we already have started. So, let me quickly go through whatever the things we have discussed, but before that just to align ourselves with the overall plan the weekly plan where are we compared to our overall plan.

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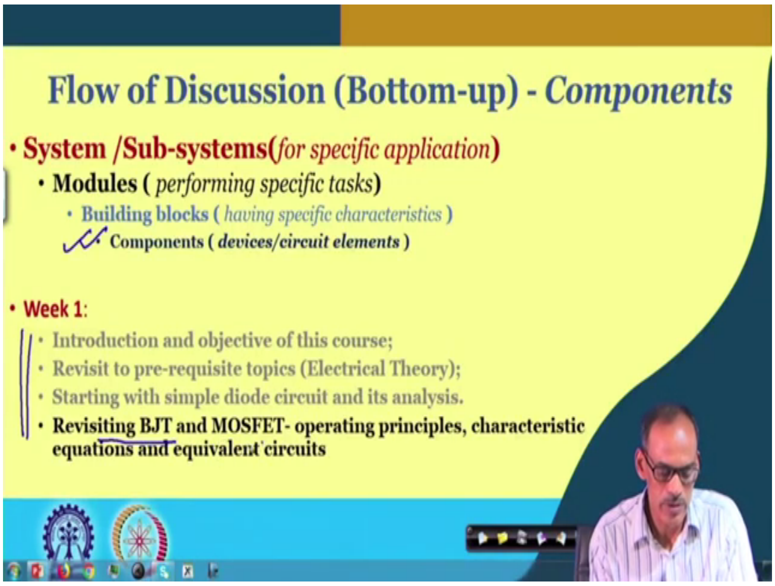

We are at present we are at component level discussion; particularly active device and in the in this week what we are at is we are going through the BJT operating principle, characteristic and all and then we will be moving to this one in the subsequent class.

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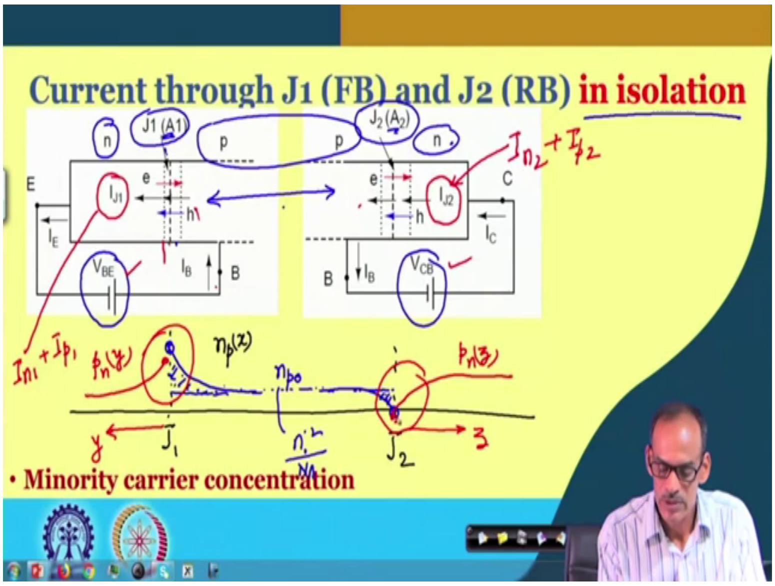

So, what we have discussed about the BJT? So, BJT particularly say n-p-n transistor it is having three regions namely n, then p region and n region. In between it is having junction, junction 1 and also junction 2. They may be having different cross sectional area A 1 and A 2. And, for active region of operation J 1 particularly one of these junctions to be forward biased by this voltage; base to emitter voltage and this junction on the other hand; it will be reverse biased.

So, the polarity of the V CB it is such that the n region, it is at higher potential than the p region. So, whenever you are talking about these two junctions biased and if we say that these two are wide apart and they are not influencing each other; then whatever the minority carrier concentration we have seen in particularly in the p region; it is having a exponential change.

So, if you see the minority carrier concentration with respect to say J 1; so we do have J 1 and likewise we do have J 2. And, since J 1 it is forward biased the minority carrier concentration namely n p in the; in the base region may be as function of x, there what we have observed that; in the neutral region it will be reaching to the level of n p 0; depending on the doping concentration in the base region will be getting n p 0 which is equal to n i square divided by N A ok; so that may be aware of.

But near the junction beyond the depletion region for the time being I am considering this depletion region is small. So, beyond this depletion region, it is having exponential penetration of the carriers and or other carrier concentration it is exponential. So, this exponential change of the minority carrier concentration it is of course it is characterized by the length up to which the electrons are penetrating namely l n and the height here it depends on how much the forward bias we do have; so that also we have discussed. Today and also once we consider the second junction which is in reverse bias condition; the minority carrier concentration it drops to 0 because of the reverse bias; I should say approximately 0.

So, there is also a change of this minority carrier concentration with respect to J 1. So on the other hand, the minority carrier concentration on the side of the junction; it is see similar it is also having similar profile. So, here also it is having a similar kind of profile namely this is p n as function of whatever it is see many distance z; z starts from this point and; so, likewise here we do have p n y minority carrier in the emitter region starting from this point. So, this y it is starting from the age of the depletion region.

So, whatever it is the behavior of this junction and behavior of this junction namely the junction current I J 1; it is exponential function of V B. So, likewise in this junction also the I J 2; it is having exponential dependency on V CB, but since it is reverse bias, you may say that approximately this current is having almost reverse saturation current time. And it is having two components; one is current carried by electrons I n 1 plus and then current carried by holes I p 1. So, likewise this is also having two current components I n 2 plus I p 2.

Now, so with this information now what we are trying to do is that we are reducing this distance and we like to see what may be the consequences. Keeping of course, J 1 forward biased and J 2 reverse bias namely physical distance of these two junctions we are trying to reduce which means that this characteristic and this characteristic they may interfere with each other.

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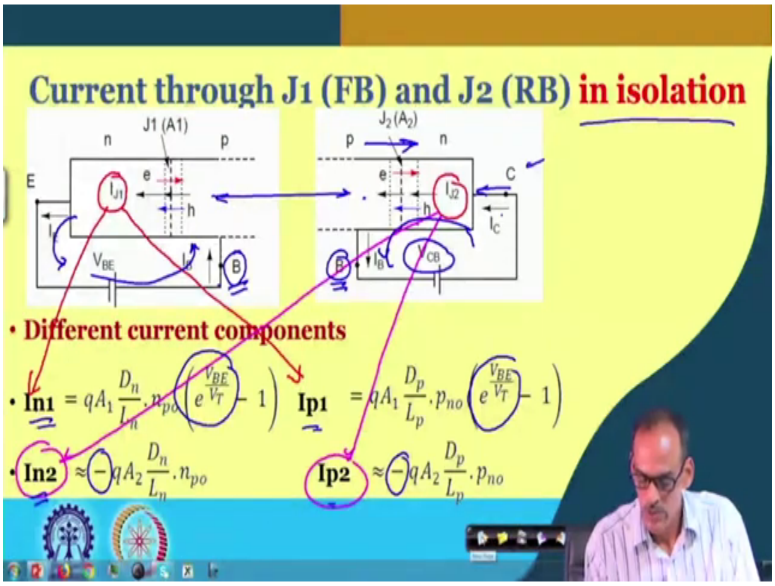

So, let us see what may be the consequence ok. Before we go into that as I said that there are different current components; we already have mentioned that this I J 1, it is having two current component namely the current carried by electrons and current carried by holes. So, likewise I J 2 it is also having two current components namely we do have I n 2 and then we do have I p 2. And it may be noted that this junction since it is forward biased; it is having very good exponential dependency on the V BE; both I p 1 and I n 1.

On the other hand, since this junction it is reverse bias; the corresponding current here it is very I mean, it is getting saturated and we may say that this these two currents are almost equal to the saturation current; remains almost independent of the reverse bias condition. Also the convention wise, we are assuming that the positive current it will be flowing from p to n, but since we are applying the reverse bias here the actual current it is flowing from n to p. So, that is why you do have these two; these two currents are having negative sign.

But whatever it is; the actual current here in this case it is flowing entering the current is entering into the collector terminal, it is departing the base terminal. On the other hand, here the current is departing from the emitter terminal and then it is entering to base terminal. So, note that this base and this base they are actually same terminal which means that at this terminal we do have this current and this current together. So, by considering different junction current component; we may be able to easily get the terminal current namely this current I E; it is a summation of these two currents. So, likewise I C; it is summation of these two currents and I B; it will be summation of these two minus whatever these two currents are there.

Now, still we are keeping the two junction since in isolated condition. Now, if I take these two junctions close to each other; let us see what are the things are happening.

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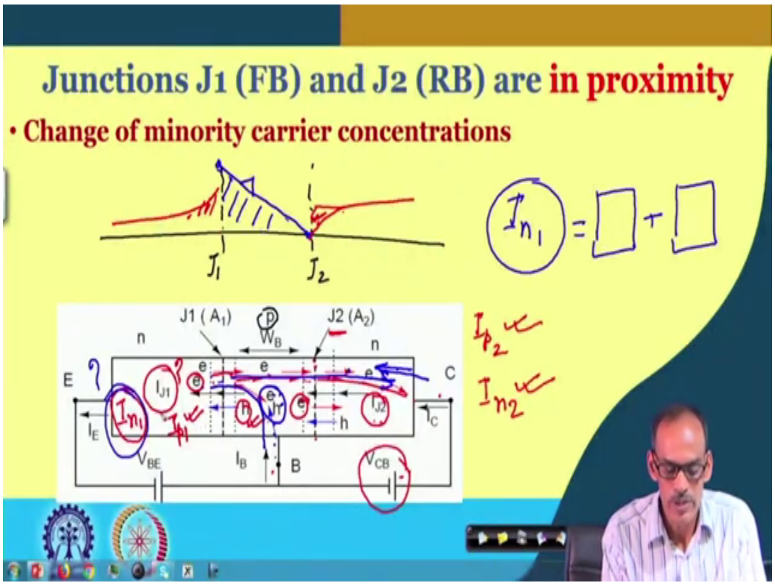

So, what we have done here it is we have taken these two junctions in the near vicinity. And, due to that the interesting change of the minority carrier concentration; particularly in the p region the base region you see; so we do have the J 1 and J 2 and if I, if I ignore for the time being if I ignore the depletion region and as you may recall in from the previous discussion; here it was supposed to be exponential fall and here it is going to 0. And since this spacing is very small practically it is going like linear of course, it will not be exactly linear; it will be having little bend here.

So, definitely because of this change of the minority carrier concentration; the slope of this characteristic at this point and this point may not be changing significantly. However, if you see the other two minority carrier concentration particularly in the; in the collector region its be the profile it remains like this. And similarly in the emitter region also the profile of the minority carrier beyond the depletion region elements like this which indicates that probably the current carried by holes in this J 2 junction as well as in J 1 junction; they will remain unchanged. Whereas, now the current carried by electron in this junction and this junction; it is anticipated to be getting changed.

So, if you see; so the total I J 1 and this junction current and this junction current, they will be as I said that they will be having two component one is due to the electrons and another is due to the holes; they do have you know they are getting changed. Particularly this is not changing this is remaining unchanged, but this is getting change. So, why is it change? Because whatever the electrons are penetrating in the base region; they are just experiencing a strong electrical field in the near vicinity across this junction.

So, as a result instead of electrons are really going into the terminal B; they may be attracted to the towards the collector region. So, pictorially here we are trying to illustrate that so many electrons; so many electrons whichever is crossing here are actually getting collected to the collector terminal. So, this whatever the red color arrow indicates that many of these electrons are getting attracted by this collector terminal; that is mainly due to the strong reverse bias and mainly due to this junction in the near vicinity.

So, before these electrons are really getting recombined with holes in the base region; they are quickly pulled out from the base region. So, as a result whatever the current component of this I J 1 namely I n 1; it is getting heavily affected. On the other hand of course, this I p 1; it is remaining unchanged. So likewise here also I p 2 remaining unchanged, but in fact, this part of course, I p 2; it is remaining unchanged. This electron of course, whatever the original electron it was there due to this reverse bias movement of this electrons due to this reverse bias in isolated condition that remains unchanged.

So, I should say I n 2; it is also remaining unchanged, the only component it is getting affected is this part; this part it is getting change. That is because its if you see the minority carrier profile it is heavily getting affected and the slope; it is very short indicating that a lot of currents it will be flowing. So, you may say that as I say that this current is see it is changing. So, we need to find that what will be the expression of that current; in addition to that some of those electrons are getting recombined. So, whatever the holes it is there in the base region it is getting recombined with whatever few of those electrons here.

So, the current carried by electrons it is actually it is having two components; one is it is getting recombined with the holes coming from this base region namely it is contribute in the base terminal current. On the other hand, the other component it is basically electrons are moving here which is contributing additional current of the collector terminal.

So, this current whatever the currents you are getting due to the penetration of the electrons; we will be calling injection current. So, the electrons are getting injected here and also it is having recombination currents. So, you may say that I n 1; fate of this I n 1, it is getting changed to two parts. One is maybe injection current which is contributing to the collector and then also it is having recombination current which is of course, it is contributing to the base terminal current.

So, let us look into a little detail of that of these two different current components. So, from this one what we have learned is that this minority carrier concentration it is getting affected and also the corresponding junctions currents are also getting modified.

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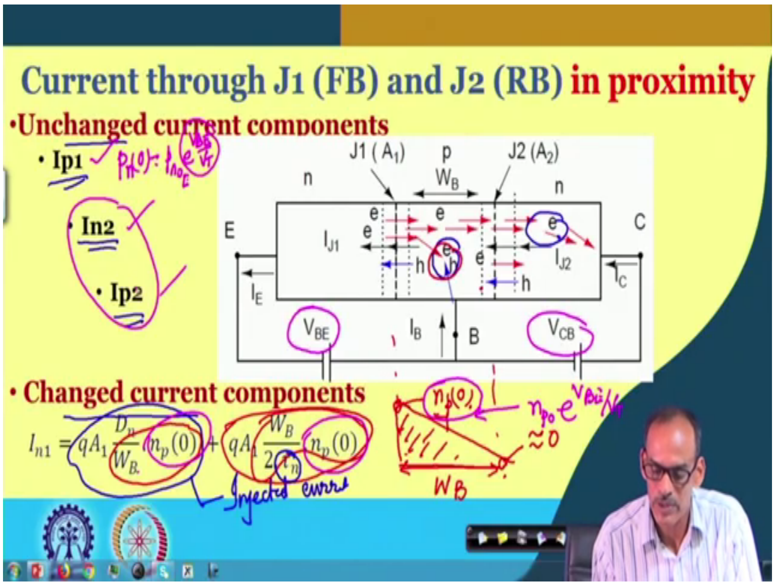

This is yeah this is what I just now we are talking about the recombination current and whatever the current we do have here; whatever the electrons are penetrating here that will be discussing. But before that as I said that I p 1 remain unchanged, I n 2 and I p 2 are remaining unchanged. The changed current components are the following. So, this is what the current which we will say that many of these the electrons are coming here. So, you may say that this is the injected current; so injected current and this part the second part on the other hand; it is the recombination current.

So, if you see its expression here; so this part is representing the gradient of the minority carrier in the in the base region. So, at this point we do have n p at distance 0 and at this point; we do have n p reaching to 0 because if the reverse bias condition there and the distance here it is base width. So, from that you may say that the gradient here. So, this is n p 0 at distance 0, this is approximately 0; so the slope here it is n p 0 divided by W B. So, that indicates the whatever the current it is coming to the collector due to the; the injected electrons from the J 1; is its expression is given here.

On the other hand, while this recombination is happening it depends on how much the electrons are available here and they are minority. So, they in fact they dictate the rate of the recombination and if I say that the shape of the concentration here in steady condition; it is like a triangular shape. So, the available charge here it is n p at 0 into W B by 2. So, this indicates the available carrier from there and tau n on the other hand it indicates the lifetime of the electron before they are getting recombine.

So, they are again contributing the base terminal current and interestingly both of these terms are function of n p 0. So, this is; this is what the important point is that this is n p 0 and this n p 0 we know that this is exponential it is having exponential dependency on the V BE by V T; so which means that both of the terms are having exponent; exponential dependency.

These two parts of course, they are almost constant; on the other hand this is have this is also having exponential dependency on V BE; that of course, it is due to some other reason namely p n at y is equal to 0; it is p n 0 in emitter into e to the power V BE by V T. So, all of them are luckily I mean most of them are luckily function of V BE exponential function.

Now, if I has said that these two currents are very small if; so even though they are only function of V CB; probably we may ignore particularly in the active region of operation; so, to further consolidate different current components and try to see the terminal current.

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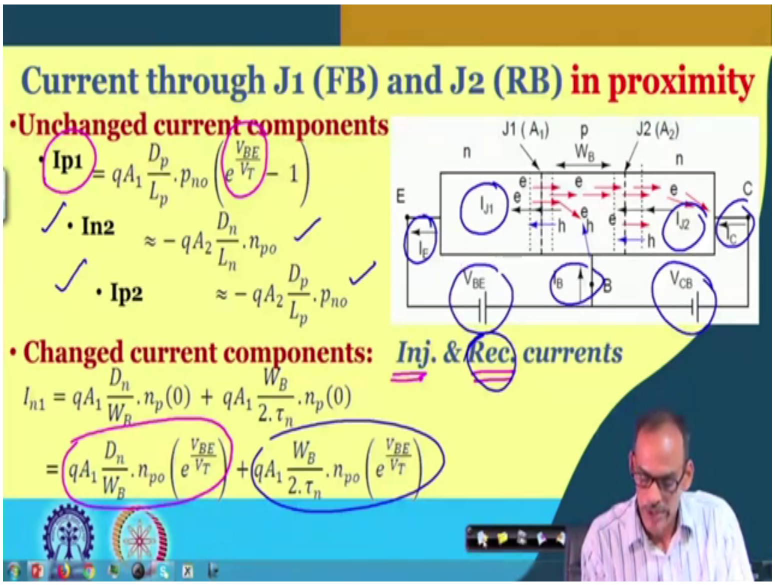

So, let us look into what are the terminal currents you do have ok; these are the expression of the current and quickly; so this is what just I was telling that one I p 1; it is exponential it is having exponential dependency of course, it is having a minus 1 part. The injected current; so this is also having exponential dependency on the V BE.

Recombination part, that is also having exponential dependency on the V BE. So, all of them are having exponential dependency; these two currents they are since it is as I say it strongly reverse biased by V CB, they are approximately independent of V CB and incidentally these two currents are also very small compared to the other component.

So, that makes the approximate I-V characteristic simpler; in other words that most of the current components. The current components of this one, current components of this one or even this terminal current components are the practically they are exponential function of V BE. So, let us look into the different terminal current.

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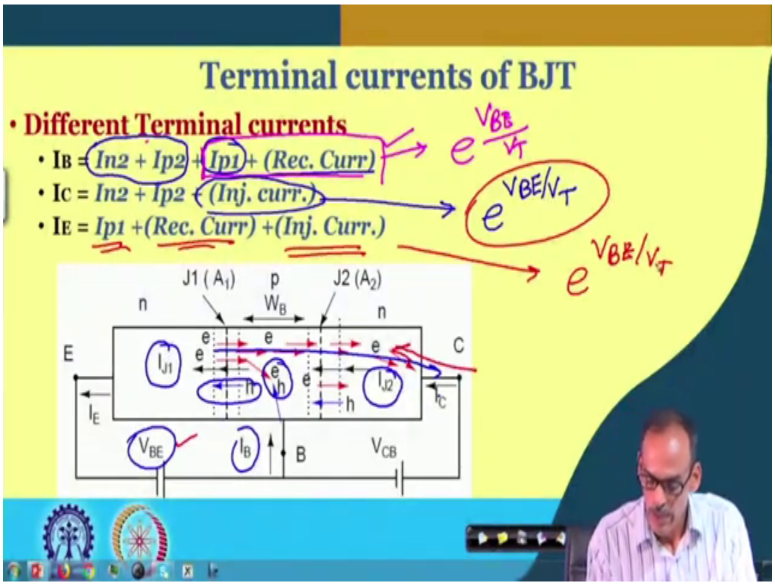

So, as I say that the base terminal current; it is summation of the two current components of this one; namely I n 2 and I p 2. These two indicates the second junction current this is this basically the junction current and also we do have I p I p 1. So, this I p 1; it is again part of this one and that is due to the movement of the holes that is of course, it is not getting change. In addition to that, whatever the d combination it is happening that current is also mentioned here.

So, this terminal current incidentally of course, these two currents are very small and also they do have a negative sign. So, if I say that with that assumption if I say that these two currents are dominating over the other two and if I approximate that the I B currently it is a function of I mean it is having dominant terms of I p 1 and then recombination current and both of them are having exponential dependency on V BE. It may be having different constant part, but what is the important thing is that it is having exponential dependency.

On the other hand, the collector current the collector current is having as I say that in the injected current namely whatever the movements of this electrons coming here; they are contributing in this terminal current. So, this part under certain condition; this is also dominating and this current it is again exponential function of V BE; that is because the availability of the carrier here, it is it depends on how much the bias you are putting and then how much the electrons are really crossing this junction.

So, from that you can say that this current particularly the injection current at the at the collector terminal; it is basically the exponential function of the V BE. And emitter current of course, I p 1 then recombination current and then the injection current; all of them are again exponential function of the V BE ok. So, all of them as I said, that all of them are having this dependency on V BE in the exponential form.

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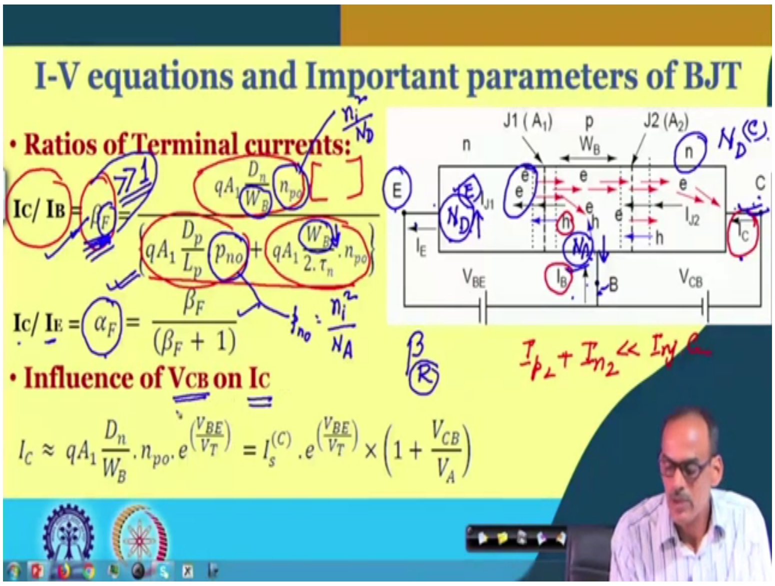

Now, if we consolidate this information and write the expression of the different current components, that gives us useful information namely I-V equations of the; the BJT. So, so far some extent we are engrossed within the device, but end of it what is important is that the terminal current and the terminal voltage. And, this slide particularly here we are summarizing the important current components. What we have it is they say that I C and I B then I E. So, all of them are having exponential dependency.

So, if we recall the previous; so if you recall here that all of the current components are having exponential dependency and so what we can say that this is having exponential dependency, this is having exponential dependency and this is also having exponential dependency. Particularly, if I draw this one part; if I approximate that this is very small compared to the other part. So, all of them are having exponential dependency.

So, as the exponential part is present it is available everywhere; the next thing is that what may be the constant part associated with each of this current component? So, let us look into their relative value and yeah. So, what we can say that if we; if we take the ratio of the collector current and base current. So, the collector current of course, it is having that exponential part; ignoring of course. So, here we are ignoring that I p 2 and I n 2; they are very very small compared to injected current. And so in the in the numerator; in the expression of the collector current, we do have only this part which is due to the injection of the electron crossing the emitter junction, base emitter junction reaching to the collector terminal through the collector junction.

On the other hand, base current is also having its own coefficient where this part is it is coming from the recombination this part is the current due to the holes here. So, this ratio this ratio defines the ratio of the collector terminal current and base current; it defines one important parameter called beta, beta F to be more precise.

So, beta indicates that; if you are injecting a current here probably you are getting a current here which is having same signature. And interestingly the device typically it is done in such a way that this is much higher than 1 which indicates that if you are injecting a small amount of base current, you can get amplified current at the collector terminal.

And this is the basis of how this circuit is working; this beta normally it is also referred as current gain because you may say that this is my input terminal, this is my output terminal; the ratio of these two are indicating the current gain. So, now if I the next thing is that why it is called beta F. This F stands for forward direction; it may be noted that we do have this emitter region and also the collector region; both are n type and also to achieve this; to get this value very high what you have to do that we have to make this part as small as possible.

So, how do we achieve that? One of them it is reducing this base width indicating that if the base width is narrow most of the electrons it will be getting collected there right. So in fact, it is having impact here as well also if you see here we like to make this is as high as possible and this is p n 0. So, p n 0 is nothing, but n i square divided by N A. In fact, if you see here not only you do have p n 0; we also have n p 0. This n p 0 on the other hand; it is also function of n i square, but it is having N D.

So, to achieve this high value of this beta what we can do; this region this region, it can be highly doped compared to whatever the doping concentration in the base region; so compared to N A. So, by doing this one what we are doing is we are making from this equation you can say that we are making this beta is as high as possible. In other words, you can see that for a given amount of current most of the current it will be carried by electrons if this is much higher than N A.

So, that is also another way of saying that for a given junction current most of the currents are carried by electron which means that with a small amount of base current; we can get high amount of this electron current which are finally, it is getting collected here. So, that is how intuitively we can say that from by these two methods namely increasing this N D and by decreasing this N A; relative you know you know relative value of this N D should be much higher than N A to achieve this beta as high as possible. And also the base width you should be as small as possible so that most of the electrons are getting collected by the collector terminal.

Now, why do we have forward direction? That is because the doping concentration of this n region on the other hand; this is also having donor concentration; this donor concentration in the collector region it is on the other hand it is much smaller than the emitter region. So, by mistake or just for your curiosity in case if you are pretending this collector as the emitter and emitter as collector in actual device; what you will be getting is that the corresponding beta it will be different, where the this condition namely the donor concentration in the emitter region should be much higher than acceptor concentration in the base that may not be getting satisfied.

Due to that, if you are connecting the device other way namely collected as emitter and emitter as collector; the corresponding current gain beta it will be different and that beta it is known as beta in the reverse direction ok. Just to I am just mentioning this one so that in hardware while we will be constructing the circuit; you should be very careful that you need to understand which is emitter and which is collector, then only you will get the correct value of the current gain,

And this the I C divided by I E; this ratio it is also indicating that what may be the current ratio of this I C and I E. This ratio of course, it is having a parameter called alpha; this name is alpha and also it is having both forward direction and reverse direction. It can be easily seen that this alpha, it is a strong function of beta because you can consider the whole device as single node and if I have only these three terminal current. So, this terminal current can be expressed in terms of I C and I B and I C and I B; they have their own relationship defined by this beta.

So, from that you can say that if I apply k c l at the device and if I use this relationship from that I can find the expression of alpha. It is having some meaning; later on we will discuss about this one, but let we move on to the other interesting thing that the collector current as I; as I say that it is having strong dependency on V BE, but it is also having weak dependency on the reverse bias.

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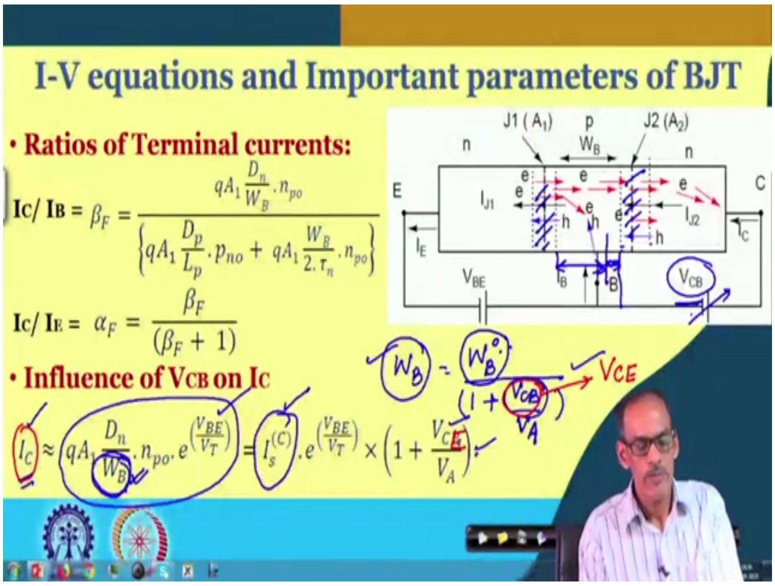

So, let us see how it is getting influenced by the reverse bias voltage at the V BE. So, we do have this V BE; first of all the collector current we are approximating by this component dominating namely the injection current and where we do have the W B. So, this base weight it is basically the residue base weight after deducting and the depletion region both in the emitter junction and the collector junction.

Now, if I increase this voltage then base width here since it is reverse bias; so this depletion region it will be getting increased; as a result this base width it will come down. So, you may say that if I increase the corresponding base width it will be narrowing down. So, if you see in this equation if the base width it is getting decreased with the increase of V CB. So, naturally the overall current it will be getting changed. So, that part the dependency part of this W B on the V CB can be well approximated by linear equation and that can be rearranged in this form.

So, you may say that if I; if I model this W B in terms of say W B naught divided by 1 plus V CB divided by V A ok. So, this may this model it is fairly note that V A it is just a; just a coefficient I should say it is a parameter fitting parameter and I may say that W B naught, it is unchanged. However, W B change of this W B with V CB can be expressed in this form and so if I use this equation here what I can get is that this factor; it it comes in the numerator and this part it can be consumed within this part which may be considered as constant term.

So, this constant term it is having W B naught and also the other parameter and the dependency on the terminal voltage it has been taken out; so that we can get the I C as function of the V BE and V CB. And for practical purposes V CB instead of using V CB; we may use V CB plus V BE so that again with again with meaningful approximation for our convenience; this do get replaced by V CE approximately ok. So, the equation of the current collector current; it is actually instead of V CB, you may write it is V CE; that is what in the textbook we write. So, what we have done here it is so with this modification; so let me write only V CE part.

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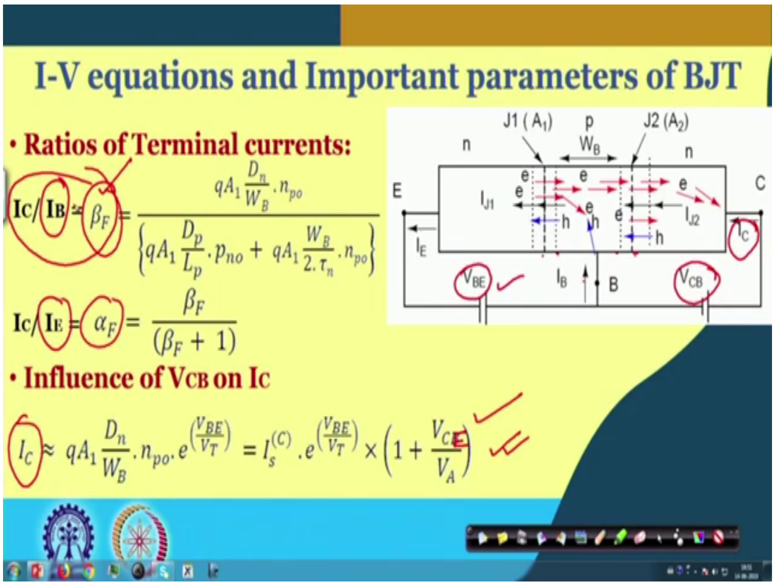

So, we do have expression of I C, we also have relationship of say I C and I B. So, if I know this parameter; if I know this expression and if I know this parameter I can find the expression of the emitter terminal current, base terminal current and also the collector terminal current. So, as a circuit designer while you will be using this device as a circuit designer; what we are looking for is that what may be the terminal current as function of these voltages? So, what may be this current particularly I C as function of V BE and V CB; that is what it is important.

So, here whatever the things we have covered till now; it is a little bit towards the device. But I think it is important to understand that little bit about the device so that while we are designing a circuit we make sure that we give a respect to the conditions to get whatever the equation we are using. Namely junction 2 should be reverse bias, junction 1 should be in forward bias condition and also whatever the devices are there just to understand, that if I put say two junction back to back; that will not form the BJT rather their base width, it is playing very important role which is also playing important role to define the important parameter; parameter called the current gain.

So, let me take a break here and we will come back how we just to see that how these equations the consolidated equations can be utilized for designing analog circuit.

Thank you.